RESEARCH DEPARTMENT

The choice and location of sound absorbers for the reduction of noise

RESEARCH REPORT No. B-083

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Digest of a Lecture delivered to a Course on 'The Techniques of Noise Reduction' at the Royal College of Advanced Technology, Salford, September 7th 1962.

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SUMMARY

The factors affecting the performance of a sound absorber in an enclosure are reviewed. These factors include the extent to which the absorbers are subdivided, the location of the separate areas and the diffusion of the sound field.

The performance of so-called 'functional' absorbers is examined, and claims that these absorbers make more efficient or economical use of absorbing material are found to be unfounded.

1. INTRODUCTION

1.1. Scope of the Report

The writing of this report was the result of an invitation by Dr. P. Lord of the Royal College of Advanced Technology, Salford, for the author to lecture on 'Functional Sound Absorbers' as part of a symposium on the measurement and control of noise, to be held in the College on September 7th and 8th 1962. Functional Absorber is the name given by Olson[1] to a sound absorber intended to be suspended from the ceiling of an enclosure instead of being fixed to a surface and therefore having, as the name implies, a purely functional purpose without any other requirements such as good appearance or thermal insulation.

Olson claimed that a specified quantity of a suitable material would absorb sound many times more effectively if in the form of a functional absorber than if fixed to a boundary surface of the room, but experiments carried out by Research Department a few years ago failed to confirm this claim. No confirmation could be found either in published literature, and it therefore appeared that it would not be justifiable to devote a complete lecture to the subject.

There still remained a possibility, however, that the Research Department experiments had not achieved the maximum performance from the functional construction. The subject was therefore investigated theoretically to determine the relative limiting performances of various configurations of absorbing material. To do so it is necessary to take into account the effects of changes in size and position of conventional surface-mounted absorbers and of diffusion of the sound-field in the room. The first part of this report reviews the factors affecting the effective absorption coefficient of a sample of a sound-absorbing material and the remaining sections give an approximate theory of functional absorbers with experimental results on several constructions.

1.2. Application of Sound Absorbers to Noise Reduction

The purpose of sound absorbers for noise reduction is to absorb the reverberant sound energy in the enclosure. If the source of noise is in the same enclosure as the listener, sound absorption clearly cannot affect the sound energy received directly from the source, but it can reduce the reverberant sound energy which, except within a short distance of the source, is the principal component of the intensity. If the source of noise is in another room, sound absorption in the source room can reduce the total intensity at the partition between the two rooms, thereby reducing the sound transmitted, and sound absorption in the receiving room will reduce the intensity at positions remote from the partition. The factor by which the reverberant sound intensity is reduced is approximately proportional to the relative increase of absorption; thus, if the absorption in a room is doubled, the reverberation time will be halved and the mean reverberant sound pressure level will be reduced by 3 dB. The change of reverberation time can be measured very much more accurately than the reduction of mean sound pressure level, and is therefore to be preferred as a method of investigation.

The figure of 3 dB quoted in the example above is small in comparison with the fluctuations of pressure level caused by stationary waves in the room, and it may seem an insignificant improvement for so great an increase in absorption. The subjective improvement is far greater, however, since there is a reduction of confusion and interference with speech owing to the increased ratio of direct to reverberant sound from the noise source and from wanted sources in the room. Thiessen and Subbarao[2] have shown that these psychoacoustic effects increase with the noise level and are equivalent to a reduction of between 3 and 4 dB in sound pressure level (S.P.L.) in the range of noise levels normally encountered in offices, workshops and similar surroundings. The results of doubling the amount of absorption in a room is therefore to reduce the impression of noisiness by between 6 and 7 dB.

1.3. Definitions

The absorption coefficient of a material is defined as the ratio of the sound energy absorbed by a plane surface of the material to the energy incident on the surface, when it is placed in a sound field from which sound falls equally in all directions. It is implied that this coefficient is a property of the material rather than of a particular finite sample and should therefore be independent of the area or shape of the sample. This is approximately so if the sample is large enough in comparison with the wavelength of the sound but, as will be shown below, small samples give higher effective coefficients than large ones because of the effect of diffraction at the edges.

The absorption coefficients published by the N.P.L. and other testing bodies are usually obtained from measurements on samples of the order of 10 m^2 area. These coefficients differ significantly from the limiting value for large areas but are equally inapplicable to situations in which the absorbing material is applied in small areas.

For some purposes in this report it will be convenient to specify the absorption of a finite object by its 'absorbing cross-section'. This may be defined as the area of an absorbing material with unity absorption coefficient which will absorb an equal amount of energy from a sound field in which it and the finite object are both placed.

The definition of the absorption coefficient of a material requires that the sound should be incident equally from all directions. This implies a state of perfect diffusion in the room, which is defined as the condition in which the energy density is uniform throughout the room and that all directions of wave motion are equally probable at all points. As both the measurement of sound absorption coefficients and their application must take account of the diffusion of the sound-field, published absorption coefficients can be regarded only as a guide. Accurate prediction of reverberation time or noise reduction from the acoustic treatment requires also detailed consideration of the size and shape of the absorbing areas and on their distribution in so far as it affects the diffusion.

2. CALCULATION OF ABSORBING CROSS-SECTIONS

2.1. The General Case

Before discussing absorbers of widely varying shape and size, we will first examine the process of absorption itself. Good approximations can often be achieved in calculating the performance of an absorber by means of analogous electrical circuits. This method has been described in previous reports and publications.[3]

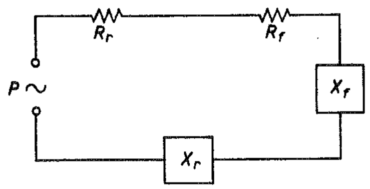

Fig. 1 - Analogous Electrical Circuit of Simple Sound Absorber

p = Sound Pressure
R_r, R_f = Radiation and Internal Resistance
X_r, X_f = Radiation and Internal Reactance

Fig. 1 shows a circuit analogous to a simple absorber in which all the elements of the acoustic input impedance can be regarded as lumped constants.

The power dissipated in the absorber (R_f, X_f) is given by[3]

$$\frac{P^2 R_f}{(R_r + R_f)^2 + X^2} \tag{1}$$

and if X is small compared with ($R_r + R_f$) as in a deep layer of a purely resistive material or in a resonant system at its frequency of resonance, the dissipation is

$$\frac{P^2 R_f}{(R_r + R_f)^2}$$

giving a maximum value of $P^2/4R_r$ where $R_f = R_r$, i.e. the correctly matched condition.

For unit area of plane-wave sound field $R_f = \rho c$ and hence the dissipation by unit area of an infinite plane sheet of a perfect absorber is $P^2/4\rho c$. (2)

The ratio of the maximum possible absorption of any other absorbing body with radiation resistance R_r to that of unit area of perfect absorbers is therefore $\rho c/R_r$; in other words, this ratio represents the number of units of area of a perfect plane absorbing surface to which the body is equivalent in absorption, provided that the internal or dissipative resistance of the body is correctly matched to the radiation resistance, i.e. its maximum potential absorption in terms of what Sabine called 'open window' units.

This quantity will be called the maximum absorbing cross-section of the body. It is inversely proportional to the radiation resistance and therefore reaches high values for bodies smaller than or comparable with the wavelength of the sound; as an example, the radiation resistance of a circular body with a diameter very much smaller than the wavelength λ is given by $2\pi\rho c/\lambda^2$.[3] Hence in these conditions the maximum absorbing cross-section is $\lambda^2/2\pi$ irrespective of the size of the hole.

2.2. The Effect of Diffraction and of Sample Size

If we can accept this last statement, it is very much easier to understand the profound influence which diffraction has on the absorption of sound by small areas of materials. Acceptance of the idea often causes difficulty and we will therefore examine the behaviour of the system shown in Fig. 2(a). A small hole occupies, say, one hundredth of the area of one end of a cylinder, the other end of which is closed by a piston which is moved in and out at very low speed.

Imagine that the hole is initially blocked, so that as the piston moves the pressure in the cylinder oscillates about atmospheric pressure. In doing so, potential energy is stored and is released in forcing the piston back to its equilibrium position. The situation represents a sound wave with peak energy density equal to the maximum stored potential energy, reflected from the wall.

Now suppose the hole be opened and a resistance inserted of such a magnitude that the energy density in the cylinder is exactly halved. It is clearly possible to find a suitable resistance since by choosing a sufficiently low frequency and resistance the peak pressures could be reduced to any chosen value, however small. The situation now corresponds to the presence of a perfect absorber covering the whole end of the wall, which would eliminate the reflected beam, and the hole is therefore seen to have an effective absorbing cross-section one hundred times its own area.

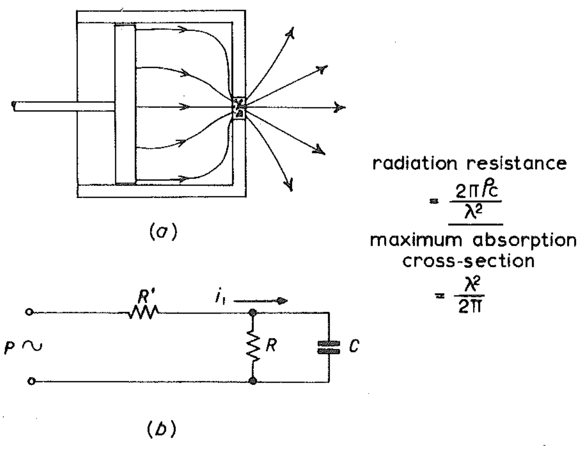

Fig. 2 - Absorption of Sound by an Aperture very small in Comparison with the Wavelength

(a) Resistive aperture with free air behind

(b) Analogous electrical circuit

To transfer this situation to mathematical terms the system may be represented by the electrical analogue of Fig. 2(b). R represents the resistance of the hole and C the compliance of the cylinder volume. R' is a very high resistance maintaining a substantially constant current i which represents the acoustic volume displacement of the piston.

The rate of energy dissipation in R is given by

$Ri^2/\{1 + (\omega CR)^2\}$, which reaches a maximum of $\frac{1}{2}Ri^2$ when $\omega CR = 1$.

The voltages across C are then given by

$\frac{i}{\sqrt{2}\omega C}$ with the hole open and

$\frac{i}{\omega C}$ with the hole blocked (R made infinite)

The mean energy density in the cylinder, being proportional to the square of the pressure is thus doubled by closing the hole, corresponding to the acoustic case of total absorption considered above.

The argument above applies only to very low frequencies of oscillation of the driving piston since for air to flow through the hole, curved streamlines are required in all parts of the volume not directly opposite the hole and these introduce inertial forces which increase as the frequency rises. At very high frequencies, only those parts of the wavefronts in the immediate vicinity will be affected by the hole, the effective cross-section of which will be reduced to a limiting value equal to its geometrical area.

This argument may be used to derive the expression already given for the maximum absorbing cross-section of a small hole, viz. $\lambda^2/2\pi$. For instance, if the frequency is 100 c/s, $\lambda = 3{\cdot}4$ m and the absorbing cross-section is $1{\cdot}84$ m^2, equivalent to a circle of diameter 48•4 cm. If the frequency is raised to 1000 c/s, the equivalent circle will have a diameter of only 4•8 cm.

To summarise, diffraction can greatly increase the unit-area absorption of a small body relative to that of a large area of the same material; this is particularly so if the acoustical impedance of the material of the body has a low value.

Diffraction likewise increases the effective absorption near the edges of a large area of a material, and this may be expected to produce an incremental absorption cross-section approximately proportional to the periphery of the sample.

3. IMPLICATIONS OF DIFFRACTION IN THE MEASUREMENT OF ABSORPTION COEFFICIENTS OF MATERIALS

It is clear from the foregoing that the diffraction effects at the edges of samples will influence the measurement of absorption coefficient of materials when carried out in the usual way by measuring the change in reverberation time of an empty room when the material is introduced. The unit-area absorption coefficients

thus derived will be greater if the sample is divided into small areas than if it is in one piece.

This is, of course, a very important consideration in deciding how the absorption coefficient of a material should be measured in a reverberation room. The International Standards Organisation has recently succeeded in reaching international agreement, largely as a result of the efforts of Professor Cremer of Germany and Professor Kosten of Delft who have been active in organising comparison measurements of identical samples between many different laboratories throughout the world.[4]

The next figure (Fig. 3) shows the way in which the sample area affects the measured absorption coefficient. It shows curves of absorption coefficients

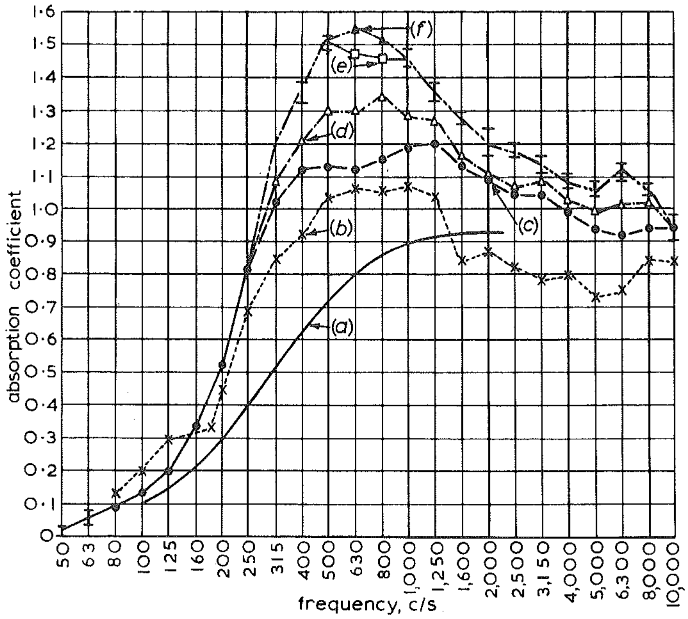

Fig. 3 - Effect of subdivision of sample on measured absorption coefficient (From W. Kuhl[5])

(a) Infinite-area coefficient derived from Impedance Tube measurements
(b) Reverberation Room measurement on sample of 10 m² area (5 m x 2 m), edge length 14 m
(c) Measurement on sample in halves (edge 24 m)
(d) Measurement on sample further subdivided (edge 30 m)
(e) Measurement on sample further subdivided (edge 40 m)
(f) Measurement on sample further subdivided (edge 60 m)

published by Kuhl in a recent paper in ACUSTICA.[5] He took a sample 5 m x 2 m (10 m^2) of Sillan rockwool 5 cm thick and measured it first of all complete so that it had a free edge length of 14 m; curve (b) shows the result. He then divided it into halves and spaced them apart from each other, then measured them again, obtaining curve (c) and so on. Curves (d) to (f) were obtained with successive further subdivision of the sample and it can be seen that at middle frequencies and above, the apparent absorption of the sample is greatly increased as the free edges are increased.

The lowest curve, (a), is a theoretical curve for the coefficient of absorption of the infinite area sample derived from measurements on part of the sample at normal incidence in an impedance tube. Kuhl showed that by expressing the absorption coefficient of each size of sample at any particular frequency as a function of its ratio of edge length to area and then drawing the graph of this relationship and extrapolating it back to a relative edge length of zero it was possible to obtain an approximation to curve (a). That is, however, not the full story and for the details reference should be made to his original paper.[5]

He also showed that the diffraction effect is greatest with materials of low impedance and least with very hard materials. This is in accordance with the view of diffraction as being a bending of the wavefront from the hard parts of the boundary to the soft absorptive parts.

The next figure (Fig. 4) illustrates the application of these ideas to the standardisation of a method of measuring the absorption coefficient in reverberation rooms. A full account of these measurements is given in a recent Research Report.[6] Curve (a) is again the statistical absorption coefficient for an infinite area derived from impedance tube measurements using the same type of material as that on which Dr. Kuhl worked. Curve (c) represents measurements on the same material as that of curve (a) using samples of a total area of 12 m^2 divided into four patches which were placed on four surfaces of the reverberation room. It will be seen that there is a high peak at 500 c/s which is due to diffraction at the edges of the sample.

Curve 4(b) was measured with the whole sample in one piece lying on the floor of the reverberation room, additional measures being introduced to ensure

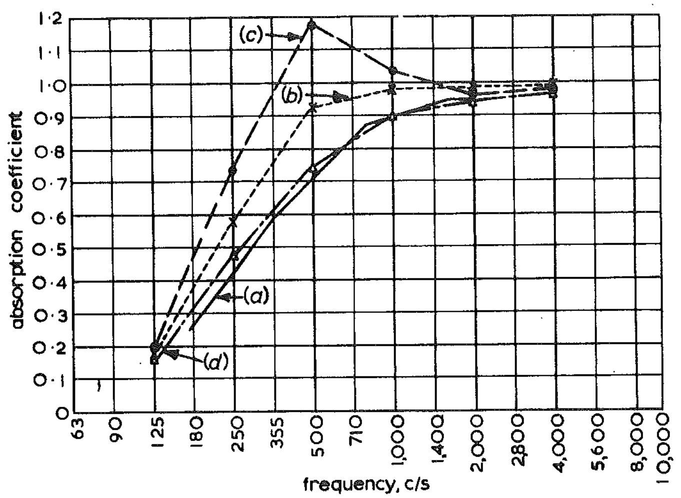

Fig. 4 - Effect of Diffraction on Measured Absorption Coefficients

(a) Coefficient derived from impedance measurements
(b) Reverberation Room measurements on whole sample
(c) Reverberation Room measurements on sample divided into four equal areas
(d) Reverberation Room measurements with one wall of room completely covered with sample

good diffusion in the measurement room. In this case the peak as such has disappeared and the curve has come about halfway down towards curve 4(a) which is assumed to represent the material without edge effects. Curve 4(d) is interesting; it was obtained with approximately the same area of sample arranged to cover entirely one wall of the reverberation room. The mounting of the sample in this way converts it in effect into an infinite area because there are no free edges. This method has been put forward by Høy[7] as a possible method for standardisation and it certainly appears to be the only method so far proved which eliminates edge effects altogether.

The method used for the compromise curve 4(b) has now, however, been adopted as an international standard for the measurement of reverberation absorption coefficients. The function of such a standard is to provide a reliable comparison between different materials even if the measurements are carried out in different laboratories. Figures published as a result of measurements made according to this standard would enable any material to be compared with any other for any particular application.

It should be emphasised, however, that where accurate calculation of the effect of acoustic treatment is required it may not be sufficient to depend upon these figures. For instance, broadcasting studios must have good diffusion and therefore, as will be shown later, the absorbing materials must be distributed in patches on several surfaces of the studio for the best results. Experience by the BBC establishes that there is very much better correlation between calculation and measurements if the materials have been measured by the divided sample method represented by curve 4(c).

4. THE EFFECT OF DIFFUSION OF THE SOUND FIELD ON ABSORPTION

The second factor which must be taken into account in connexion with the measurement and use of absorbing materials is the state of diffusion in the room. It has been pointed out that calculations of reverberation time assume a state of complete diffusion in the room whereby any area of absorber receives an equal density of sound energy falling on to it. If the diffusion is poor, the sound energy will be concentrated in a few directions, and the usual result is that the efficiency of the absorber is low. In fact, this may be used as a measure of diffusion.[8] As an example, consider a corridor in which the ceiling height is large compared with the wall areas and the ceiling has been covered with some sort of sound absorber. There will be unlimited opportunity for the sound to cross from side to side of the passage without being absorbed and it is only sound travelling up and down which will be immediately absorbed. The transfer of energy from one direction to another takes place comparatively slowly and therefore the efficiency of the ceiling absorber will be low.

Fig. 5 shows what happens to a single sample of absorber in a bare room. The lower curve represents the sample measured in these circumstances with no attempt to improve the diffusion in the room. At low frequencies there is a steep rise in absorption coefficient whereas at frequencies above 250 c/s it falls off steadily.

The upper curve shows the result of hanging sheets of hardboard with a total area of 36 m^2 from the ceiling of the room. This helps to break up the wave-

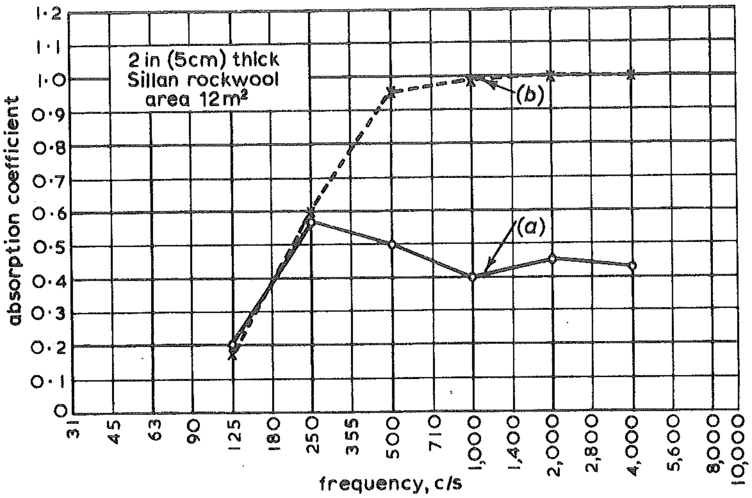

Fig. 5 - Effect of Diffusion on Absorption of Single Sample in Bare Room

(a) No diffusers (b) 36 m² of diffusers

fronts of the sound in the room and increase the rate of transfer of energy from one direction to another. The result is a very great increase in the measured absorption coefficient or, in other words, the efficiency of the absorber. These sheets of hardboard are described as diffusers - that is, means for improving the diffusion of the sound field. Other types of diffuser are irregularities in the wall surfaces or ceiling which are very often made cylindrical or spherical but are possibly best made rectangular in shape. The most efficient type of diffuser is possibly a patch of absorber which acts strongly in the frequency region at which diffusion is desired. Thus if the sample is distributed as a number of patches on, say, three or four of the surfaces, there is an immediate increase in the diffusion of the room and each of the patches will be affected by the diffusion produced by the others.

The next figure (Fig. 6) illustrates this. It shows the results of measurements on the same material as that represented in the last two figures but divided this time into four patches; the lower curve shows the result when there are no hardboard panel diffusers present and the upper curve shows the result of

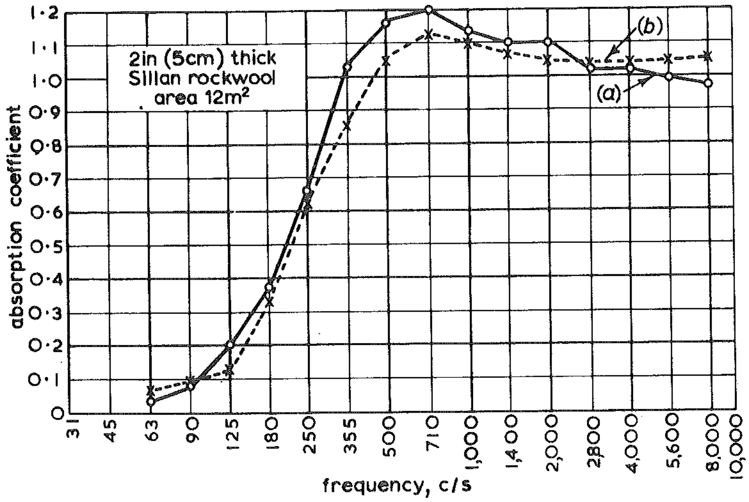

Fig. 6 - Effect of Diffusion on Absorption of Distributed Sample in Bare Room

(a) No diffusers (b) 36 m² of diffusers

adding 36 m^2 of hardboard panels. It will be seen from this curve that even in the absence of the added diffusers the diffusion of the room is already great enough to make nearly full use of the absorbers.

Noise reduction problems are not in general associated with buildings equipped with elaborate means of diffusion. The usual situation is a corridor, an office or a workshop in which the walls are substantially flat and the ceiling is either flat or pitched with large unbroken surfaces. Therefore in attempting to make the best use of the absorbing material careful attention must be given to distributing it so as to produce an appreciable amount of diffusion. Where the ceiling is high it may be valuable to add some areas of absorber on the walls as well.

In this connexion the special effects of corners and edges of a room should be mentioned. It is often said that these are the best places for absorbing material because the mean sound pressure due to standing wave systems can be shown to be twice as much along an edge as in the centre of a wall and again twice as much in a corner as along an edge. This certainly leads to better performance of absorbers at low frequencies because the size of the region which may be regarded as a corner or edge is naturally related to the wavelength and will be large at low frequencies. At high frequencies, on the other hand, the areas of room surface effectively in the corners or edges is small. Moreover, it is found by experiment that corner- or edge-sited absorbers do not improve the diffusion of the sound-field as do those sited elsewhere, and they consequently absorb less efficiently than they otherwise would.

The next figure (Fig. 7) gives the results of a typical experiment which shows the distinction between the behaviour of absorbers in different parts of the room. The corner-sited absorbers have a distinct advantage at low frequencies but become extremely inefficient in comparison with edge- or face-sited absorbers at higher frequencies.

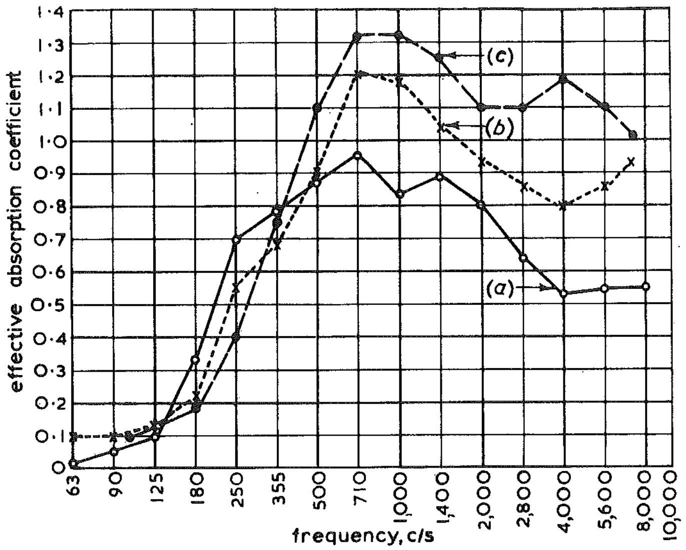

Fig. 7 - Absorption of sound by material in different situations in a room (small patches)

(a) In the corners (b) In the edges (c) On the surfaces

5. FUNCTIONAL ABSORBERS

5.1. Early Work on Functional Absorbers

We now turn to a type of absorber in which there has been considerable interest during the last few years, that is, absorbers in which the material is not hung on the wall but is suspended remote from the ceiling and receives sound from all directions. It has been claimed on occasions that such a method of applying a specific amount of absorbing material is far more efficient because the maximum possible use is made of the effects of diffraction. The expression 'functional absorbers' appears to have been first employed by Olson in 1948[1] who used the term to indicate that the sole function of the absorber was to absorb sound and that therefore there was no need for compromise with respect to aesthetic or structural considerations. Olson described experiments on absorbers consisting of hollow shells of compressed fibrous material and his results showed that the efficiency was approximately doubled when compared with the same material nailed on to battens as a single sample, 72 ft^2 (6·8 m^2) in area, laid on the floor. The effective absorption coefficients for functional absorbers, that is, based on the area of their surfaces, was 1·4 or even higher.

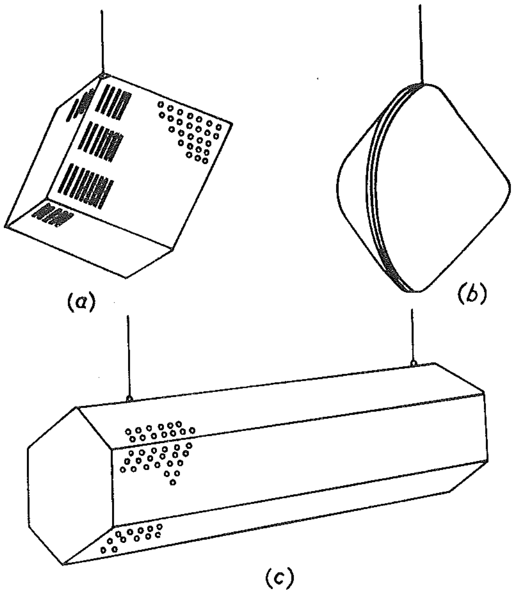

Fig. 8 - Functional Absorbers

(a) Cubical (BBC, Abramchik and Maletskii[9])

(b) Fibrous double cones (Olson[1])

(c) Hexagonal section cylinders (Darlington Insulation Company)

Fig. 8 shows various types of functional absorber. The type used by Olson consisting of double cones is represented in Fig. 8(b). The left-hand sketch at the top shows a form on which experiments have been done by Abramchik and Maletskii[9] in Poland and by ourselves at the BBC. In both cases the covering was a perforated hard material, like metal or hardboard, and the absorber was lined with mineral wool, the type shown in the lower picture will be referred to in Sections 5.2.2. and 6 below. Typical results obtained by Olson are shown in Fig. 9. The upper two curves, 9(a) and 9(b), are for functional absorbers consisting of double cones of 14 in (35 cm) and 7 in (18 cm) diameter respectively. The lowest curve, 9(c), is for samples consisting of 72 ft^2 (6·8 m^2) of the same material placed edge to edge and nailed on to battens. There are two points which should be noted about these curves. Firstly, as shown by the previous figures, had the material been subdivided into patches of an area similar to that of the individual functional absorbers, very much higher absorption coefficients for curve 9(c) would have been obtained, particularly in the region of 500 c/s. Secondly, at upper frequencies, above 2000 c/s for instance, the wavelength of the sound is considerably shorter than the dimensions of the absorbers and therefore diffraction effects would not be present to any great

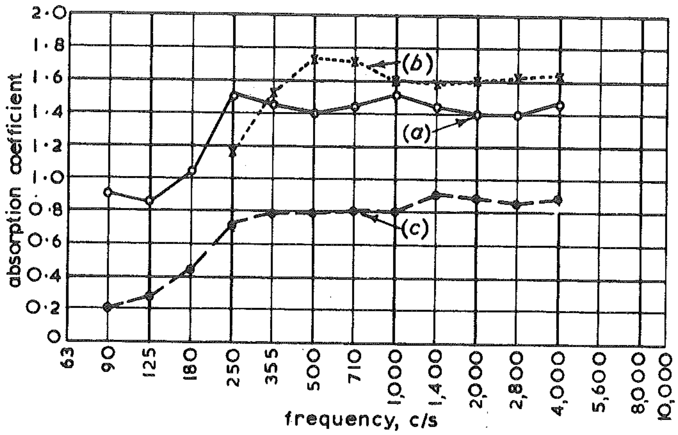

Fig. 9 - Effective Absorption Coefficient of Double-Conical Functional Absorbers (drawn from Olson's data[1])

(a) 14 inch (35 cm) diameter cones

(b) 7 inch (18 cm) diameter cones

(c) 72 ft^2 (6·8 m^2) of the material laid on the floor

extent. It is therefore rather surprising to find the great difference between curves (a) and (b) on the one hand and curve (c) on the other.

Much more modest results were obtained by Abramchik and Maletskii[9] in Warsaw using cubes made of perforated metal filled with rockwool. These cubes have a side of 1 ft (30 cm) and therefore an area of 6 ft^2 (0·55 m^2). The results are shown in Fig. 10 and it is clear that these authors were unable to obtain nearly such high coefficients of absorption based on the surface area of the absorbers as those claimed by Olson.

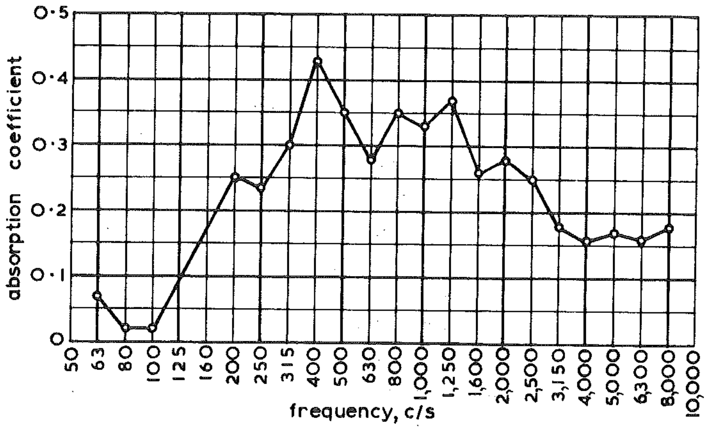

Fig. 10 - Effective Absorption Coefficient of Cubical Functional Absorbers (re-drawn from data by Abramchik and Maletskii[9])

The same may be said of the BBC results on cubes of 16 in (40·6 cm) side made of perforated hardboard lined with rockwool. The next figure (Fig. 11) shows the effective absorption coefficient of the material used in this way with that from a comparable material measured in the form of flat samples of 24 ft^2 (2·3 m^2) area. The highest coefficient is obtained from the flat material. Unfortunately, though this material was comparable with that in the cubes, it was not exactly the same because the 1953 material used with these cubes was no longer obtainable.

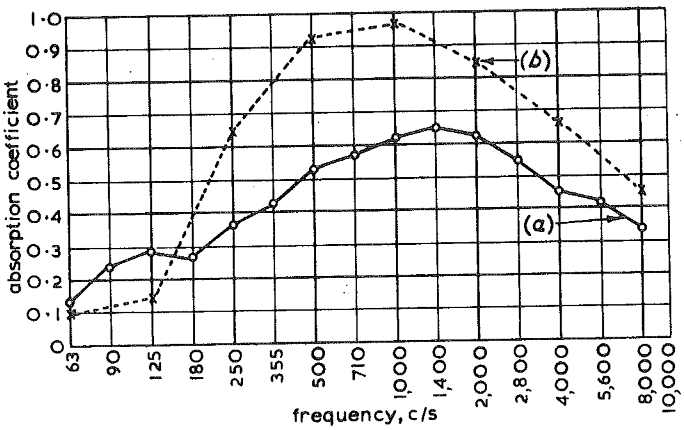

Fig. 11 - Comparison between effectiveness of materials in cubical of flat arrangement

(a) Effective Absorption Coefficient of Cubical Functional Absorbers
(b) Absorption Coefficient of Comparable Material Measured as Flat Sample

5.2. Simple Theory of Functional Absorbers

This is a convenient point at which to pause to see how one would expect material used in the form of functional absorbers to compare in its absorbing efficiency with the same material laid flat on the surfaces of the room. Without trying to make exact calculations, one can derive quite useful information by applying the general principles governing sound absorption by a body as previously discussed.

Consider the behaviour of the material in one of these absorbers: first, at very low frequencies where the wavelength of the sound is very large compared with the dimensions of the absorber so that the pressure of the sound wave is almost uniform in amplitude and phase at all points on the surface; secondly, at intermediate frequencies where the sample is comparable with the wavelength in its dimensions; and thirdly at high frequencies where the wavelength is small and diffraction effects are therefore negligible.

5.2.1. Spherical Functional Absorbers

For simplicity, consider a functional absorber, consisting of a spherical shell of porous material of radius r, in each of the three frequency ranges just described.

At very low frequencies the radiation resistance is half that quoted in Section 2.1. for a hole in an infinite plane, since the absorber receives radiation equally from two hemispheres of space instead of one.

i.e. $$R_r = \pi\rho c/\lambda^2 \qquad (3)$$

Hence the internal resistance R_a per unit surface area for a correct match is given by the equation

$$R_a/4\pi r^2 = \pi\rho c/\lambda^2$$

and therefore

$$R_a = 4\pi^2\rho c r^2/\lambda^2 \tag{4}$$

The maximum possible absorbing cross-section of the absorber is given by

$$\rho c/R_r = \frac{\rho c\lambda^2}{\pi\rho c} = \frac{\lambda^2}{\pi}$$

Hence, since the area of the material is $4\pi r^2$, the maximum effective coefficient of absorption, α_{eff}, is

$$\lambda^2/4\pi^2 r^2 \tag{5}$$

If we suppose, for example, that $f = 200$ c/s, $c = 3{\cdot}4 \times 10^4$ cm/sec, $r = 20$ cm, $\rho = 1{\cdot}23 \times 10^{-3}$ g/cm^3, we have

$$R_a = 23 \text{ dyne/cm}^2\text{/sec}$$

$$\alpha_{eff} = 1{\cdot}82$$

In the above calculation, the impedance of the absorber is assumed to be entirely resistive, but since the volume enclosed in the shell is finite there will be a series capacitive component, reducing the flow through the material and hence its absorption.

The volume per unit surface area is

$$\frac{4}{3}\pi r^3/4\pi r^2 = r/3 \tag{6}$$

The acoustic capacitance of this volume is calculated as follows: the compression modulus of a volume V for adiabatic volume changes is $\gamma P_o/V$ where P_o is the static pressure and γ the ratio of the specific heats.[10]

The acoustic capacitance is the inverse of this, and thus is $r/3\gamma P_o$ for a volume of $r/3$.

But $c^2 = \gamma P_o/\rho$ and hence the required acoustic compliance per unit area of the surface of the sphere is

$$r/3c^2\rho \tag{7}$$

At 200 c/s this gives a reactance of 170 c.g.s. units per unit area.

From equations (1) and (2), the absorbing cross-section of an absorber having a series reactive component X is seen to be

$$\frac{P^2 R_f}{(R_r + R_f)^2 + X^2} \div \frac{P^2}{4\rho c} = \frac{4R_f\rho c}{(R_r + R_f)^2 + X^2} \tag{8}$$

By differentiating this with respect to R_f, we find the maximum absorption occurs if

$$R_f = \sqrt{R_r^2 + X^2}$$

Putting $R_r = \pi\rho c/\lambda^2$, as before, and $\lambda = 170$ cm, $r = 20$ cm,

$$R_r = 4{\cdot}5 \times 10^{-3}$$

$$X = 170/4\pi r^2$$

$$= 3{\cdot}18 \times 10^{-2}$$

Then $$Rf = 3{\cdot}5 \times 10^{-2}$$

Substituting these values in (8), the maximum absorbing cross-section is

$$0{\cdot}46 \text{ cm}^2 \text{ per cm}^2 \text{ of surface}$$

This result is higher than those shown in Figs. 9 and 10(a), though still lower than that of a comparable porous material tested as a flat sample (Fig. 10(b)).

By the introduction of a resonance to neutralise the reactive term, higher values over a limited frequency band are possible. Example of this will be shown later.

At medium frequencies, say 1 kc/s, effects due to the reactance of the finite volume are negligible and any element of the absorber receives sound from a large part of one hemisphere. In this respect it behaves as a patch of absorber of similar diameter on the wall and may thus be evaluated by interpolation in Fig. 3. However, unlike the patch on the wall, it is exposed to sound from two hemispheres. Each half of the absorber has twice the surface area of the wall-mounted disk of the same diameter. The maximum possible absorption per unit area of material is therefore similar to that of a wall-mounted disk of the same projected area, i.e. $0{\cdot}12$ m^2. From the evidence presented in Fig. 3, high values of the coefficient are therefore possible.

Lastly, at frequencies so high that diffraction can be neglected, the material behaves as if it has a constant cross-section from all directions, unlike the wall-mounted disk of which the aperture varies with the direction of incidence.

The area of capture of a sphere of radius r is πr^2, irrespective of the direction of the incident sound. A disk of the same radius mounted on a wall, however, presents an area of $\pi r^2 \cos\theta$ to sound incident at angle θ with the normal to its plane.

Imagine a hemisphere of large radius R_o in the sound field with its centre at the centre of the disk. The proportion of sound from a diffuse sound field incident at angle θ is then proportional to the area of an elementary ring of infinitesimal width $R_o\, d\theta$ subtending an angle θ with the normal.

This area is $2\pi R_o^2 \sin\theta d\theta$.

The mean area of capture for randomly incident sound is thus

$$\frac{\pi r^2 \int_0^{\pi/2} 2\pi R_o^2 \sin\theta\cos\theta d\theta}{\int_0^{\pi/2} 2\pi R_o^2 \sin\theta d\theta} = \tfrac{1}{2}\pi r^2$$

i.e. half its actual area

This mean area applies only to sound coming from one hemisphere whereas the sphere receives sound from both hemispheres. The effective area of capture for the sphere and the disk are thus in the ratio 4 : 1, i.e. in the same ratio as their actual surface areas.

A specified area of material will therefore receive and absorb sound energy at the same rate whether it is mounted flat on a wall or formed into a spherical functional absorber.

To sum up the foregoing argument, one may say that if we make a given area of a material into a spherical functional absorber instead of spreading it out on a wall, it will not in general yield any greater coefficient of absorption. Just as with wall-mounted absorbers, high coefficients may be obtained for limited frequency bands by introducing resonances, and though at mid-frequencies high coefficients may be expected due to diffraction they will be no higher than those for wall-mounted material divided into patches of similar area.

5.2.2. Cylindrical Functional Absorbers

If the material is made up into prismoidal or cylindrical shapes, with one dimension substantially greater than the other two, better results may be expected, as shown by the calculations following below.

At low frequencies the absorber may be considered as a long narrow strip. The radiation resistance per unit area of an infinitely long strip in a plane is $\pi\rho c/\lambda$[11] and hence for the line source in free space.

$$R_r = \frac{\pi\rho c}{2\lambda} \tag{9}$$

The maximum absorption with a matched resistance is therefore

$$\rho c . \frac{2\lambda}{\pi\rho c} = \frac{2\lambda}{\pi} \text{ per unit length}$$

and the maximum absorption per unit area of surface (effective absorption coefficient of the surface) is

$$\frac{2\lambda}{\pi} . \frac{1}{2\pi r} = \frac{\lambda}{r\pi^2} \tag{10}$$

Proceeding as for the spherical case in 5.2.1. above we have for f = 200 c/s and r = 20 cm, taking into account the reactive component for which the volume per unit surface area = $r/2$, α_{eff} = 0·56 and R_f (optimum) = 114.

Thus the cylindrical shape gives a higher efficiency than the spherical and requires a less dense material. Introduction of inductive components by suitable coverings to the material will increase the effective coefficient in a limited frequency band and thus may make it equal to or greater than the values obtained with a flat layer. Similarly, at medium frequencies the cylinder gives an absorption comparable with that of a long strip of material on the wall.

At high frequencies the mean capture area of a long cylinder (length l) is given by the expression.

$$\frac{1}{\pi R_o^2}\int_0^{\pi/2} 2rl\pi R_o^2\cos^2\theta d\theta, \text{ using the notation of Section 5.2.1.}$$

$$= \tfrac{1}{2}\pi r l, \text{ which is one quarter of its actual surface.}$$

As it is suspended in free space, its effective mean capture area, compared with a wall-mounted strip, is doubled, thus becoming one half its actual surface area. This is identical with the mean capture area of a flat wall-mounted lamina of the same surface area, as calculated in Section 5.2.1. above.

To summarise, a cylindrical functional absorber may be expected to have an absorbing cross-section at medium and high frequencies equal to that of a strip of wall-mounted material of the same length and area. At low frequencies for which the wavelength is very much greater than its radius, it will have a better performance than a sphere, but not necessarily better than a flat layer of material on a wall.

6. MEASUREMENTS ON PRISMATIC ABSORBERS

Measurements were carried out on various modifications of a prismatic functional absorber, with the kind co-operation of Mr. G. Pearson and the Darlington Insulation Company who provided the absorbers and carried out the modifications.

The absorbers were, for convenience, made hexagonal in cross-section, the outer shell being of perforated aluminium with an open area of 25%. Fig. 8(c) shows the shape. Their length was 6 ft (1·8 m), and the side of the cross-section was 8½ in (21 cm). This shell was lined with rockwool 1½ in (3·7 cm) thick, with a flow resistance of 40 c.g.s. units. Measurements were made, first with the rockwool alone and then with calico or paper diaphragms between the perforated cover and the rockwool. The results are shown in Fig. 12. Curves (a), (b) and (c) are the measured values of the effective absorption coefficient of the surfaces, first of all with the rockwool only, secondly with the paper membrane behind the cover and thirdly with the calico membrane. Curve (a), for the rockwool only, follows very closely curve (e) which is the absorption coefficient curve obtained from a flat sample of the same material in the front of a 2 in (5 cm) air space,

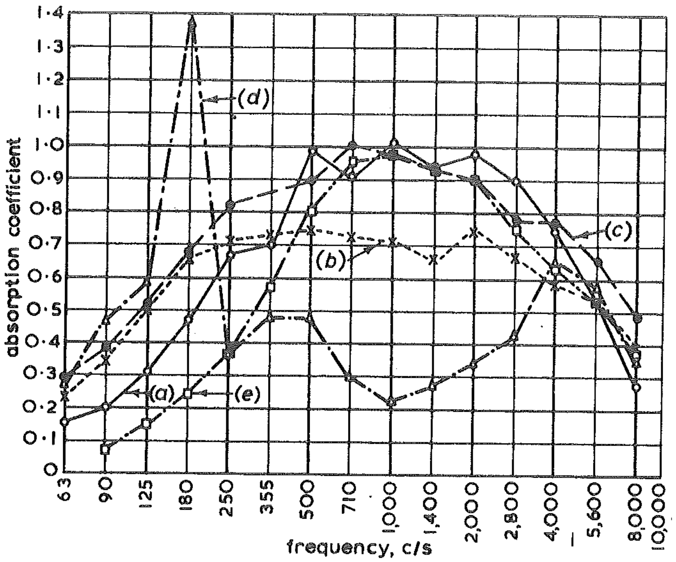

Fig. 12 - Effective Absorption Coefficient of Hexagonal Cylindrical Functional Absorbers (Absorption Cross-section per unit surface area)

(a) Rockwool only behind perforated metal cover
(b) With paper membranes in front of rockwool
(c) With calico membranes
(d) As (c) but tested in corners of room
(e) H.D.S. Rocksil 1 inch (2·5 cm) deep over 1 inch airspace with 5% perforated cover

measured by the normal BBC method; there is very little difference at the upper end of the frequency scale but at low frequencies the functional absorber shows a distinct advantage. The addition of the paper membrane (curve (b)) produces a broad resonance at low frequencies, the mass of the paper and capacitance of the air underneath being the relevant parameters, and so extends the curve at the bass end at the expense of the upper frequency end where the opacity of the paper to sound at high frequencies becomes effective. Curve (c) is for a compromise using a calico diaphragm of somewhat high flow resistance, which was found to increase the absorption coefficient in the bass and middle frequency regions without affecting the top. Curve (d) is of some interest; it was obtained for the calico membrane absorbers placed in the corners of the room. In this condition there was a resonance of the whole system at about 175 c/s which enabled the absorber to act as a pure resistance. These results, together with the general arguments which have been presented, show that the use of the material in the form of functional absorbers does not confer any very remarkable properties upon it. This applies particularly for noise suppression where it is generally more useful to have a good middle- and high-frequency performance.

On the other hand, the use of free-hanging rather than wall-mounted absorbers may have some independent advantages. First, in these experiments the functional absorbers showed every evidence of promoting good diffusion in the reverberation room irrespective of their position. The consequence is that they may be used efficiently in the situation where there is, for example, a high ceiling and where the walls cannot for some reason be used for the location of sound absorbers.

Secondly, of course, they may be used in buildings such as factory workshops using roof lighting where in many cases the ceiling cannot be used for ordinary flat absorbers without appreciably diminishing the area available for lighting, and where the walls are used for equipment. Thirdly, they can be used where the construction of the walls or ceiling make the fitting of the ordinary absorbers inconvenient.

Against these independent advantages must be set the consideration that conventional sound absorbers are mostly, by reason of their physical properties, good heat insulators as well as sound absorbers. The use of functional absorbers where conventional absorbers could equally well be used may necessitate the provision of extra heating.

Fig. 13 is a photograph of functional absorbers used for noise reduction in a teleprinter room in the Langham Office Block near Broadcasting House, London.

Fig. 13 - Cylindrical Functional Absorbers hanging from ceiling of Teleprinter Room

7. CONCLUSIONS

1. Sound absorbers for the reduction of noise in rooms can affect only the reverberant sound, and their objective effect is therefore a reduction of 3 dB in

the reverberant component only for every doubling of the total absorption. The subjective effect is, however, greater.

2. Absorbing materials are considerably more efficient for sound reduction if distributed over all surfaces and if subdivided into small patches, so as to improve the diffusion of the sound-field.

3. There is little advantage to be obtained from edge or corner location of absorbers.

4. The claims made for so-called functional absorbers hanging freely in the room appear to be exaggerated. The total absorption by a spherical or cylindrical object hanging freely cannot be expected to exceed that by the same material mounted on a room surface. There may be practical reasons, however, for preferring one type or the other. Cylindrical forms appear more efficient at low frequencies than spherical forms.

5. Functional absorbers appear, from the measurements described in this report, to contribute significantly to the state of diffusion in the sound-field. This may be considered a reason for using them in preference to wall-mounted absorbers in situations where diffusion is poor.

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